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Exposure of Surgeons to Extremely Low-Frequency Magnetic Fields During Laparoscopic and Robotic Surgeries

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Abstract: The development of new medical electronic devices and equipment has increased the use of electrical apparatuses in surgery. Many studies have reported the association of long-term exposure to extremely low-frequency magnetic fields (ELF-MFs) with diseases or cancer. Robotic surgery has emerged as an alternative tool to overcome the disadvantages of conventional laparoscopic surgery. However, there has been no report regarding how much ELF-MF surgeons are exposed to during laparoscopic and robotic surgeries. In this observational study, we aimed to measure and compare the ELF-MFs that surgeons are exposed to during laparoscopic and robotic surgery.

The intensities of the ELF-MFs surgeons are exposed to were measured every 4 seconds for 20 cases of laparoscopic surgery and 20 cases of robotic surgery using portable ELF-MF measuring devices with logging capability.

The mean ELF-MF exposures were 0.6 ± 0.1 mG for laparoscopic surgeries and 0.3 ± 0.0 mG for robotic surgeries (significantly lower with $P < 0.001$ by Mann–Whitney U test).

Our results show that the ELF-MF exposure levels of surgeons in both robotic and conventional laparoscopic surgery were lower than 2 mG, which is the most stringent level considered safe in many studies. However, we should not overlook the effects of long-term ELF-MF exposure during many surgeries in the course of a surgeon's career.

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Abbreviations: ELF = extremely low frequency, ICNIRP = International Commission on Non-Ionizing Radiation Protection, MF = magnetic field.

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INTRODUCTION

New electronic devices and equipment lead to increased convenience in our lives. However, there is concern about possible hazards of the electromagnetic fields that these devices and equipment produce and their effects on human health. Electromagnetic fields have the properties of both electric and magnetic fields (MFs), which have considerably different properties and possibly different ways of influencing the human body. Electric fields are easily shielded or weakened by conducting objects, even human skin, but MFs are not so easily blocked.[1] Therefore, most recent studies have focused on the health effects of MFs because MFs are not readily shielded and are easier to measure than electric fields.[2]

In 1979, Wertheimer and Leeper[3] first reported that increased development of childhood cancer was associated with proximity of the home to electrical power lines. Since then, many groups have studied the biological effects of MFs. Among the spectrum of MFs, the extremely low-frequency (ELF) MFs range from 3 to 3000 Hz and include the 50- and 60-Hz frequencies used in power lines and electric appliances,[4] classified as possibly carcinogenic to humans (Group 2B) by the International Agency for Research on Cancer.[5] The International Commission on Non-Ionizing Radiation Protection (ICNIRP) issued guidelines for limiting exposure to electromagnetic fields in 2010, and these guidelines for the general public restricted MF exposure to 2 G at 60 Hz for any length of time to limit current density to prevent effects on nervous system function.[6] However, many epidemiologic studies have suggested a more stringent 2 mG as the highest acceptable level for long-term exposure.[7–9] The guidelines by Swedish Board for Technical Accreditation for computer monitors also restrict computer monitors to produce ELF-MF of no more than 2 mG at 30 cm.[10]

Associations between ELF-MFs and diseases have been reported by many groups. Sastre et al[11] reported that ELF-MFs altered human cardiac rhythm. Furthermore, Savitz et al[12] suggested an association between arrhythmia-related cardiovascular disease and ELF-MFs, which is consistent with the previous study by Sastre et al[11] In addition to heart diseases, ELF-MFs are also associated with breast cancer. Several studies have reported that ELF-MFs increase the risk of breast cancer.[13–16] Moreover, more than 20 studies of the effects of ELF-MFs on cognitive dysfunction and dementia, including a recent 2014 study, reported a positive association between ELF-MF exposure and cognitive dysfunction.[17]

Despite increasing attention to the ELF-MF and its association with diseases, not many studies have been conducted regarding ELF-MFs in hospitals. Many electrical apparatuses are used and becoming essential for treatment and diagnosis of diseases in hospitals, but not much attention has been given to the potential risk from the ELF-MFs produced. Lee et al[18] and Roh et al[19] reported how much anesthesiologists are exposed to

ELF-MFs during surgery by, respectively, spot measurements and repetitive measurements, similar to the present study. Riminesi et al[20] measured ELF-MFs from infant warming systems and incubators in neonatal intensive care units and reported high ELF-MFs above 2 mG. Hanada[21] measured MFs higher than the ICNIRP exposure guidelines in some hospital areas.[22]

With the technological advances of the late 20th century, the concept of surgery through a scope, that is, laparoscopic surgery and minimally invasive surgery, became a reality.[23,24] Currently, the advantages of laparoscopic surgery and minimally invasive surgery, including shorter hospital stays, decreased postoperative pain, and a rapid return to preoperative activity, are well accepted.[25] Despite the benefits of laparoscopic surgery, there are drawbacks. The da Vinci Surgical System (Intuitive Surgical, Mountain View, CA) has emerged as an alternative tool to overcome the disadvantages of conventional laparoscopic surgery, such as 2-dimensional visualization and limited degrees of motion and freedom. In addition, robotic surgery systems eliminate physiologic tremors and the fulcrum effect and provide excellent ergonomics and improved dexterity.[26] Computerized enhanced robotic surgery using the da Vinci Surgical System has been used successfully in cardiac surgery, urology, general surgery, orthopedics, maxillofacial surgery, ophthalmology, neurosurgery, gynecology, and even in surgical gynecologic oncology.[27] With its increasing practical uses and significant potential promise, many studies have been published regarding costs and benefits of robotic versus conventional laparoscopic surgery in several centers with surgical robotic systems.

Most surgeons are already exposed to ELF-MFs from monitors, computers, and medical apparatuses that are placed in limited spaces. Moreover, laparoscopic and robotic surgeries, which provide benefits in terms of surgical outcome, require more devices than other surgeries and hence produce more ELF-MFs, increasing the exposure hazard to hospital staff in operating rooms, especially to surgeons. Surprisingly, there are no reports regarding how much ELF-MF surgeons are exposed to during laparoscopic and robotic surgeries. Because surgeons may be in operating rooms for a long time every day, the exposure time is also considerably long, which increases the potential hazards of ELF-MFs to surgeons. To our knowledge, this is the first study to measure ELF-MFs at the position of the surgeon's heart during laparoscopic and robotic surgeries using a robotic surgical system. Our objectives were to compare the ELF-MFs during laparoscopic and robotic surgery and to identify the source of ELF-MFs in the operating room.

METHODS

Subjects

Exposure levels of surgeons to ELF-MFs in 20 laparoscopic surgeries and 20 robotic surgeries at the Yonsei University Health System in Seoul, Korea, were measured from July to October in 2014. For robotic surgeries, the da Vinci Surgical System was used. To represent the whole robotic surgery and at the same time to fairly compare laparoscopic and robotic surgery, 2 types of surgery from the colorectal and hepato-biliary-pancreatic surgery divisions were selected. Each surgery from both divisions uses almost the same equipment in laparoscopic and robotic surgery, except the robot system is used only in the robotic surgeries. Low anterior resection was chosen in the colorectal surgery division, and cholecystectomy was chosen in the hepato-biliary-pancreatic surgery division. All subjects were informed of the purpose and procedure of the experiments and provided written consent before joining the study. The Yonsei University Health System Institutional Review Board approved the study protocol (project no. 4-2014-0398).

Measurement of ELF-MFs

To measure ELF-MF exposure levels of the surgeons, an EMDEX Lite (Enertech Consultants, Campbell, CA), a portable device to periodically measure ELF-MF intensity, was fitted in position over each surgeon's heart during each surgery (Figure 1A). The EMDEX Lite can measure ELF-MFs between 40 and 1000 Hz ranging from 0.1 to 700.0 mG with a resolution of 0.1 mG and accuracy of $\pm 2\%$. The ELF-MF intensity was sampled and stored inside the device every 4 seconds from the start to finish of each surgery. The data were then retrieved by connecting the measuring device to a personal computer and analyzed by EMCALC 2000 (Enertech Consultants) analysis and graphical software.

Statistical Analyses

The mean and standard deviation of ELF-MF intensity during each surgery were calculated. The proportions of exposure levels ≥ 2 mG in each surgery were also calculated. The Mann–Whitney U test was used to compare the mean exposures to ELF-MFs of the surgeons. The U value calculated by Mann–Whitney U test for each group is the difference between the possible minimum rank that the group can take $[n(n+1)/2]$ and the sum of the ranks in the group, where n is the group sample size. The calculations in the Mann–Whitney U test use the smallest U value of the 2 groups. The smaller the U value is, the less likely it has occurred by chance. The null hypothesis was that the mean exposures to ELF-MFs of surgeons were the same in laparoscopic and robotic surgeries. We did not accept the null hypothesis for a U value ≤ 127 (the critical value for total surgeries) and a U value ≤ 23 (the critical value for surgeries for each division), each corresponding to $P < 0.05$. All reported P values were 2-sided, and P values <0.05 were considered statistically significant. All statistical analyses were performed using the Statistical Package for the Social Sciences software (version 20, IBM SPSS Statistics; IBM Corp, Armonk, NY).

RESULTS

Tables 1 and 2 present the data including exposure levels of ELF-MFs in the laparoscopic and robotic surgeries, respectively. Table 3 shows comparisons of the mean ELF-MF exposures of surgeons in the laparoscopic and robotic surgeries. In the 20 laparoscopic and 20 robotic surgeries, the mean ELF-MF exposure was 0.6 ± 0.1 mG for the laparoscopic surgeries and 0.3 ± 0.0 mG for the robotic surgeries (significantly lower with Mann–Whitney $U = 0$, $P < 0.001$). In 8 laparoscopic surgeries and 1 robotic surgery, maximum exposure levels were ≥ 2 mG. In addition, the proportions of exposure levels ≥ 1 mG and <2 mG were 2.4% for laparoscopic and 0.1% for robotic surgeries. The proportions of exposure levels <1 mG were 97.5% for laparoscopic and 99.9% for robotic surgeries.

In the colorectal surgery division, the mean ELF-MF exposures during the 10 laparoscopic surgeries (ranging 2.9–6.3 hours in duration) and the 10 robotic surgeries (ranging

FIGURE 1. (A) The EMDEX Lite was fitted over each surgeon's heart during surgery. (B) The surgeon at the master console of the da Vinci Surgical System. (C) The operating table and surgeon during robotic surgery. (D) The operating table and surgeon during laparoscopic surgery.

1.9–3.4 hours in duration) were 0.6 ± 0.1 and 0.3 ± 0.0 mG, respectively (significantly different with Mann–Whitney $U = 0$, $P < 0.001$) (Table 3). In the hepato-biliary-pancreatic surgery division, the mean ELF-MF exposures during the 10 laparoscopic surgeries (ranging 1.1–2.0 hours in duration) and the 10 robotic surgeries (ranging 0.7–1.3 hours in duration) were 0.7 ± 0.1 and 0.3 ± 0.0 mG, respectively (significantly different with Mann–Whitney $U = 0$, $P < 0.001$) (Table 3).

DISCUSSION

Considerable attention has been focused on the association of ELF-MFs with human diseases, especially on their potential hazards regarding cancer in children, heart diseases, breast cancer, and cognitive dysfunction.[3,11,13,17] The guidelines for the wide spectrum of frequency have been established for short-term exposure by the ICNIRP and the World Health Organization.[6,28] The most stringent ELF-MF level for weak long-term exposure suggested by many epidemiological studies is 2 mG.[7–10] In one study, the mean ELF-MF exposure of anesthesiologists during surgery in a standing position was 5.8 ± 5.2 mG with 70% of them exposed to levels of ≥ 2 mG.[19] Another study done by Ubeda et al[29] reported spot measurements ranging from a minimum of 0.3 ± 0.1 mG in nurses to a maximum of 3.9 ± 1.3 mG in physiotherapists, with exposure levels of surgeons, physicians, and radiologists included in this range. Our group has also assessed the daily exposure of endodontic personnel to ELF-MFs; the mean ELF-MF exposure of 10 personnel in an endodontic section during working hours was 0.3 ± 0.4 mG.[30]

In our study, the total mean exposures to ELF-MFs were 0.6 ± 0.1 mG ($n = 20$) for laparoscopic surgeries and 0.3 ± 0.0 mG ($n = 20$) for robotic surgeries. The proportions of exposure levels ≥ 2 mG were 0.11% for laparoscopic surgeries and 0.01% for robotic surgeries. Laparoscopic and robotic surgeries showed ELF-MFs comparably lower than 2 mG, which was considered a safe limit in many studies.[7–10] Moreover, the mean MF exposures of the surgeons in the laparoscopic and robotic surgeries were lower than the mean MF exposure level of 1.1 mG in homes in North America.[31] Therefore, it can be considered safe for patients who spend a considerably short time in the operating room. However, because surgeons and hospital staff spend considerably more time in operating rooms, it would be prudent for them to avoid ELF-MF exposure elsewhere.

The ELF-MF exposures during robotic surgeries were significantly lower than those during laparoscopic surgeries ($P < 0.001$), because of the distance of the master console from the operating table. We reported in previous studies that the mean ELF-MF exposures of anesthesiologists were

TABLE 1. Exposure Levels of Surgeons to Extremely Low-Frequency Magnetic Fields During Laparoscopic Surgeries

Surgery	Duration of Measurement (h)	Number of Measurements*	MF Exposure (mG) Min	Max	Mean ± SD	MF ≥2 mG (%)
Colorectal division						
LS 1	6.3	5688	0.1	4.1	0.6 ± 0.2	0.12
LS 2	4.7	4255	0.2	1.9	0.7 ± 0.2	0.00
LS 3	4.2	3750	0.2	1.4	0.7 ± 0.2	0.00
LS 4	3.8	3392	0.2	2.3	0.5 ± 0.1	0.09
LS 5	4.2	3763	0.1	2.9	0.5 ± 0.2	0.16
LS 6	5.7	4998	0.1	2.7	0.6 ± 0.2	0.50
LS 7	4.2	3794	0.1	2.4	0.6 ± 0.2	0.13
LS 8	3.3	2936	0.1	1.5	0.8 ± 0.3	0.00
LS 9	3.7	3316	0.1	1.3	0.5 ± 0.1	0.00
LS 10	2.9	2602	0.1	1.7	0.6 ± 0.2	0.00
Hepato-biliary-pancreas division						
LS 11	1.9	1677	0.1	1.2	0.6 ± 0.1	0.00
LS 12	1.4	1224	0.2	1.0	0.6 ± 0.1	0.00
LS 13	1.5	1328	0.2	1.0	0.6 ± 0.1	0.00
LS 14	1.6	1476	0.1	2.9	0.6 ± 0.1	0.07
LS 15	1.1	981	0.1	2.1	0.5 ± 0.1	0.10
LS 16	1.4	1219	0.1	1.5	0.8 ± 0.1	0.00
LS 17	1.1	1025	0.1	1.1	0.8 ± 0.1	0.00
LS 18	2.0	1766	0.1	1.8	0.6 ± 0.2	0.00
LS 19	1.4	1305	0.1	1.4	0.6 ± 0.2	0.00
LS 20	1.5	1375	0.1	3.1	0.8 ± 0.2	0.07

LS = laparoscopic surgery, MF = magnetic field, SD = standard deviation.
*The number of measurements was counted on the basis of the repeated measurements every 4 seconds within the designated time.

TABLE 2. Exposure Levels of Surgeons to Extremely Low-Frequency Magnetic Fields During Robotic Surgeries

Surgery	Duration of Measurement (h)	Number of Measurements*	MF Exposure (mG) Min	Max	Mean ± SD	MF ≥2 mG (%)
Colorectal division						
RS 1	3.4	3027	0.2	1.5	0.3 ± 0.1	0.00
RS 2	1.9	1743	0.1	0.5	0.3 ± 0.1	0.00
RS 3	2.1	1861	0.1	0.5	0.3 ± 0.1	0.00
RS 4	1.9	1687	0.1	1.8	0.3 ± 0.1	0.00
RS 5	2.3	1998	0.2	0.5	0.3 ± 0.1	0.00
RS 6	2.2	1989	0.1	0.7	0.3 ± 0.1	0.00
RS 7	3.1	2775	0.1	3.8	0.3 ± 0.1	0.07
RS 8	2.0	1767	0.1	1.7	0.3 ± 0.1	0.00
RS 9	2.6	2369	0.1	0.6	0.3 ± 0.1	0.00
RS 10	2.5	2294	0.1	1.0	0.3 ± 0.1	0.00
Hepato-biliary-pancreas division						
RS 11	1.3	1172	0.2	1.4	0.3 ± 0.1	0.00
RS 12	1.1	989	0.2	0.6	0.3 ± 0.1	0.00
RS 13	0.9	780	0.2	0.6	0.3 ± 0.1	0.00
RS 14	1.1	994	0.1	0.6	0.3 ± 0.1	0.00
RS 15	1.0	889	0.2	1.2	0.3 ± 0.1	0.00
RS 16	1.2	1067	0.2	0.9	0.3 ± 0.1	0.00
RS 17	0.8	700	0.2	0.6	0.3 ± 0.1	0.00
RS 18	1.1	1016	0.1	1.2	0.3 ± 0.1	0.00
RS 19	0.7	612	0.2	0.8	0.3 ± 0.1	0.00
RS 20	0.7	626	0.1	0.5	0.3 ± 0.1	0.00

MF = magnetic field, RS = robotic surgery, SD = standard deviation.
*The number of measurements was counted on the basis of the repeated measurements every 4 seconds within the designated time.

TABLE 3. Comparisons of the Mean Extremely Low-Frequency Magnetic Field Exposures of Surgeons During the Laparoscopic and Robotic Surgeries

Division	MF Exposure (mG)*		*U* Value†	*P* Value
	Laparoscopic Surgery	Robotic Surgery		
Colorectal	0.6 ± 0.1 (n = 10)	0.3 ± 0.0 (n = 10)	0	<0.001
Hepato-biliary-pancreas	0.7 ± 0.1 (n = 10)	0.3 ± 0.0 (n = 10)	0	<0.001
Total	0.6 ± 0.1 (n = 20)	0.3 ± 0.0 (n = 20)	0	<0.001

MF = magnetic field.
* Values are given as mean ± standard deviation.
† *U* and *P* values were obtained by Mann–Whitney *U* test.

5.8 ± 5.2 mG with 70% of them exposed to levels of ≥ 2 mG.[19] We can infer from this study that a large portion of the ELF-MFs originate from the surgical operating table, which is close not only to the surgical equipment but also to the anesthesia and monitoring equipment. The levels of exposure to ELF-MFs from robotic surgeries showed a consistent value of 0.3 mG regardless of the different surgery divisions because the position of the measuring device to the master console is consistent for each robot system. Moreover, the mean distance between the master console of the robot system and the operating table was 440 ± 55 cm. At a distance of 90 to 120 cm from an electric appliance, the MF is at background level[2]; therefore, 440 cm is enough distance so that the MF is at background level at the master console. In addition, the master console monitor uses LCD screens, which produce a very weak MF due to the low current and power.[32,33] Therefore, the surgeon's head during robotic surgery could be exposed to only a weak MF. The ELF-MFs from the operating table and nearby equipment did not reach the master console where the surgeon sat, and we found that ELF-MFs from the master console of the robot system were 0.3 mG at the position of the surgeon's heart (Figure 1C and D).

In Figure 1B, the operator is sitting close to the master console with his head close to the monitor. Although 0.3 mG is considered a low ELF-MF exposure level, the surgeon sits at the monitor for a fairly long period of time, and not much is known about the cumulative effect of low-intensity ELF-MFs. We measured ELF-MFs over the surgeon's heart because previous studies reported harmful effects of ELF-MFs on the heart.[11,12] Although the effects of ELF-MFs on other diseases such as breast cancer and diseases associated with the brain are also well known,[13,17,34] it was most convenient for surgeons to attach the measuring devices over the heart, where it was also least likely to interfere with the surgeon's ability to operate.

Until now, it has not been clearly understood what level of weak and long-term ELF-MF is harmful to humans. Many studies have been conducted not only in animals but also in human cells to determine the toxic effects of ELF-MFs,[35] the function of electrons in DNA, and their association with the response to MFs.[36] However, more research is needed to clarify the exact pathogenesis of how weak long-term ELF-MFs affect human health, not only at the DNA level but also directly at the cell level.

With the advancement of technology, many devices have been developed for diagnosis and treatment of diseases. They have become essential tools for physicians, and as a result, hospitals now have a high density of technologically advanced instruments.[19] These instruments produce ELF-MFs that could be harmful to surgeons and medical staff who regularly spend long periods of time in the operating room. Although laparoscopic and robotic surgeries that require more electronic devices than other surgeries would produce more ELF-MFs, there have been no previous studies regarding ELF-MFs in these types of surgery. To our knowledge, this is the first study to provide basic reference data of ELF-MFs in robotic surgery compared with conventional laparoscopic surgery.

In conclusion, the exposure of surgeons to ELF-MFs in robotic surgery was significantly lower than that in laparoscopic surgery because of the distance of the master console from the operating table. Although the ELF-MF level of laparoscopic surgery was still considerably lower than 2 mG, which is the most stringent level considered safe in many studies, we should not overlook the effects of long-term exposure of ELF-MFs during many surgeries over the course of a surgeon's career. Our study has several limitations. First, the settings of the equipment can be slightly different in each surgery. However, these slightly different settings would not significantly change the ELF-MFs. Second, we do not know the exact sources of ELF-MFs during laparoscopic and robotic surgeries, but this study focuses on the ELF-MF exposure of surgeons, not on the individual devices and equipment that produce the ELF-MFs. Future studies on the sources of ELF-MFs in the operating room might be promising. Manufacturers, physicians, and associated administrators should not overlook ELF-MF exposure and its long-term effects on humans, even though the MF intensity is weak.

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